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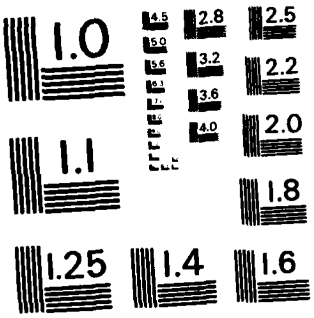

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EVALUATION OF WES ONE-DIMENSIONAL DYNAMIC SOIL TESTING PROCEDURES

by

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U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION

June 1983

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PREFACE

This report was prepared under Purchase Order DACA39-82-M-0095 for the Geomechanics Division (GD), Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES).

The report documents an evaluation of laboratory test data obtained from the explosive-loaded uniaxial strain device developed at WES and the data analysis procedures currently being used. The study was funded under Office, Chief of Engineers, RDT&E Project 4A161102AT22, Task BO, Work Unit 005, entitled "Constitutive Properties for Natural Earth and Man-Made Materials." The study was conducted and the report prepared by Dr. Lynn Seaman of SRI International.

Dr. J. G. Jackson, Jr., was Chief, GD, and Mr. Bryant Mather was Chief, SL, during the preparation of this report. The Commander and Director of WES was COL Tilford C. Creel, CE, and the Technical Director was Mr. F. R. Brown.

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ILLUSTRATIONS

INTRODUCTION

The Geomechanics Division of the Waterways Experiment Station (WES) tests soils to provide material property data for ground motion calculations in support of high explosive experiments.[1,2] Thus, the validity of the ground motion predictions depends greatly on the WES material properties used. The usual WES experiments are uniaxial strain (UX) and triaxial shear (TX) tests that can be performed at static testing rates and at dynamic rates with rise times down to about one millisecond. However, in the field experiments being simulated, the measured rise times are often 0.01 ms up to 0.1 ms. Recently, an effort has been made to obtain test data in UX and TX devices with rise times of about 0.1 ms. Some of the test data obtained at these very high rates have appeared to be anomalous, suggesting that wave propagation or other effects may be invalidating the data.

Because of these questions about the high rate soils test data, WES asked SRI to evaluate the testing methods used at WES and the data reduction device.

OBJECTIVES

The major objective of the effort was to evaluate the explosive-loaded one-dimensional (uniaxial strain) test device used for testing soil at WES. Specific objectives were to:

(1) Develop limits on the loading rise times and stress levels that can be used with the device. The properties of wet Fort Knox clay and a dry sand were used as representative of the soil properties of interest.

(2) Suggest modifications of the test device so that stresses of 0.5 kbar and rise times of 0.1 ms can be reached, and provide reliable data on the soil.

(3) Examine the data analysis procedure being used and make recommendations to improve the methods.

REVIEW OF UNIAXIAL STRAIN TEST DEVICES

The basic design of the WES uniaxial strain soil test devices was developed by Whitman[3] at the Massachusetts Institute of Technology (MIT) for dynamic testing of soils. A simplified cross section of the device is shown in Figure 1. The sample is a disk 3 to 5 inches in diameter and 0.5 to 1 inch thick. Axial stress is applied by pressurizing an oil chamber above the sample. The stress is measured by a pressure gage in the oil. An average strain is obtained by an LVDT (linear variable differential transformer) that monitors the deflection of the top surface of the soil sample. The conditions in the soil are approximately those of a uniaxial strain state. The approximations are associated with the variations of pressure and deflection across the top surface of the sample, the side wall friction developed as the soil compresses and moves down past the steel side walls, the radial expansion of the soil caused by the expansion of the steel side walls, and the nonuniform stress and strain states in the sample associated with wave propagation under high rate loading.

In the WES ram-loaded test device, the oil chamber is pressurized by nitrogen gas that acts on a steel piston above the oil chamber. Loading is suddenly applied by opening a port that allows the nitrogen (at several thousand psi pressure) to enter a chamber above the piston. For loading times in the millisecond range and shorter, large pressure waves propagate in the nitrogen chamber, and these waves result in pressure oscillations in the oil chamber. A sample pressure record exhibiting these oscillations is shown in Figure 2. The explosive-loaded UX test device of WES is similar to the ram-loaded UX device except that the loading is applied by a small explosive detonated above the oil chamber. This explosion provides a single pressure pulse with a total duration of about 1 ms. A

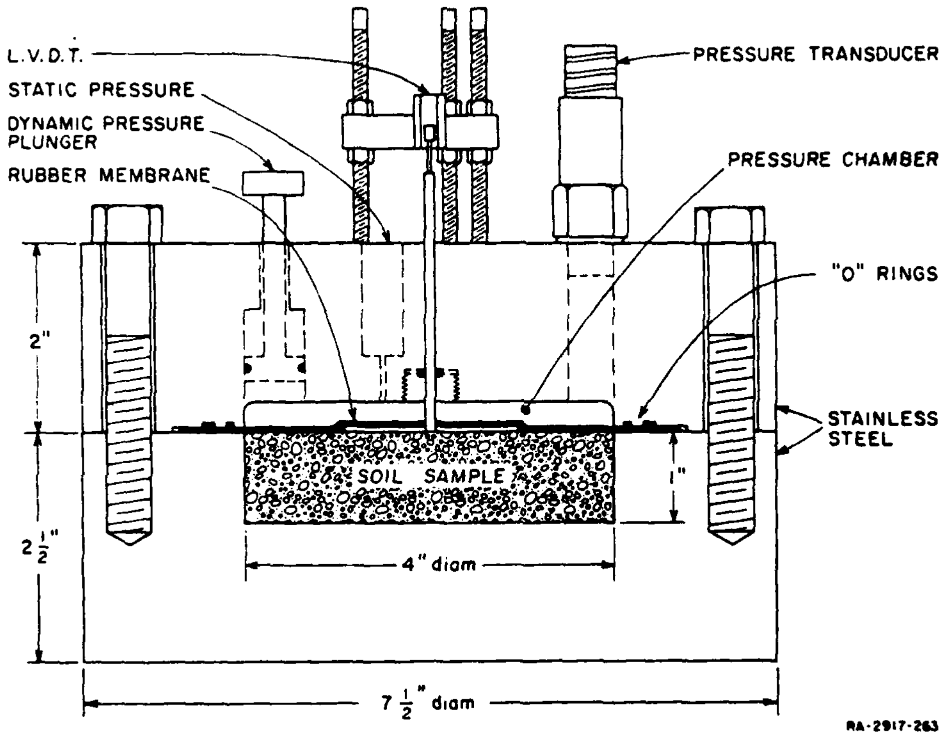


Figure 1 M.I.T. One-Dimensional Test Device

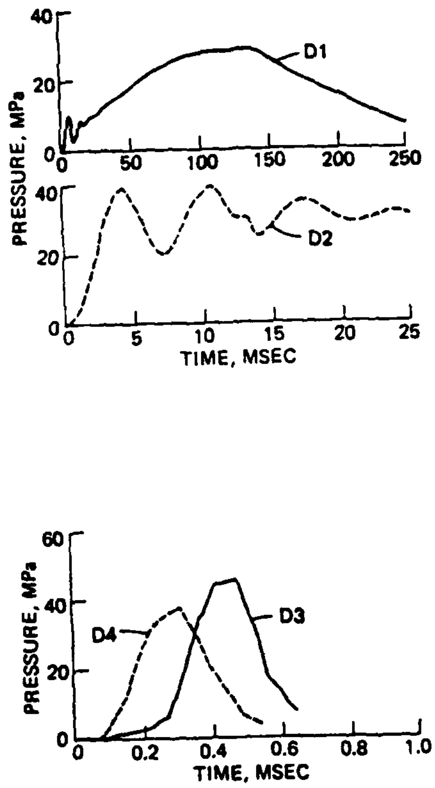


Figure 2 Uniaxial strain loading histories: Top two figures are from the ram-loaded UX device; bottom figures are from the explosive-loaded UX device (Ref. 1).

sample pressure history for this device is also shown in Figure 2.

As the pressure rises in the oil, an axial stress is created in the soil. This stress propagates through the soil and is reflected by the steel base, returning as a compression wave of increased amplitude. When the wave strikes the upper soil surface, the stress in the wave is reduced to the oil pressure, sending a rarefaction wave back into the soil. If the pressure is applied slowly (over several milliseconds), these waves of compression and rarefaction carry only small stress increments, so the soil is essentially at a uniform state throughout its depth. However, if the pressure is applied rapidly, the stress state in the soil at the steel base may be very different from that at the top surface of the soil. With such nonuniform states in the soil, the measured pressure and deflection are not representative of the soil behavior.

The following analyses were conducted to examine some aspects of the tester to determine conditions under which the measured results are representative of the material properties.

ANALYSES OF THE EXPLOSIVE-LOADED UX TEST DEVICE

Three analyses were conducted of portions of the test device to assess the range of rise times and stress levels that should be used. First, wave propagation through the soil sample was examined by simplified analytical methods. Then a one-dimensional wave propagation code was used to provide a more precise calculation of a few representative cases. Finally the expansion of the steel chamber was studied to determine the upper limit on stress loadings.

Wave Propagation Effects Within the Tester

We performed two types of analyses to examine the range of validity of the tester results considering the presence of loading rates which will cause significant wave effects. We first considered the waves reflected from the steel base, then the time delay associated with measuring stress and strain at locations other than at the midpoint of the soil sample. The combination of these two effects is treated in the code analyses in the next section.

The analysis of wave reflection effects begins with the assumptions that the materials are linearly elastic and that the loading can be represented by a series of steps in pressure. The analysis is simplified by applying these steps in pressure in time increments such that Δt equals the round-trip propagation time through the soil sample. (These assumptions are illustrated in Figure 3.) This simplification allows us to consider the interactions of one of these wavelets. When the wavelet strikes the steel at the bottom, a compression wave is reflected back into the soil with an amplitude of

$$\Delta\sigma_2 = \frac{2\,Z_{st}}{Z_{so} + Z_{st}}\,\Delta\sigma_1 \qquad (1)$$

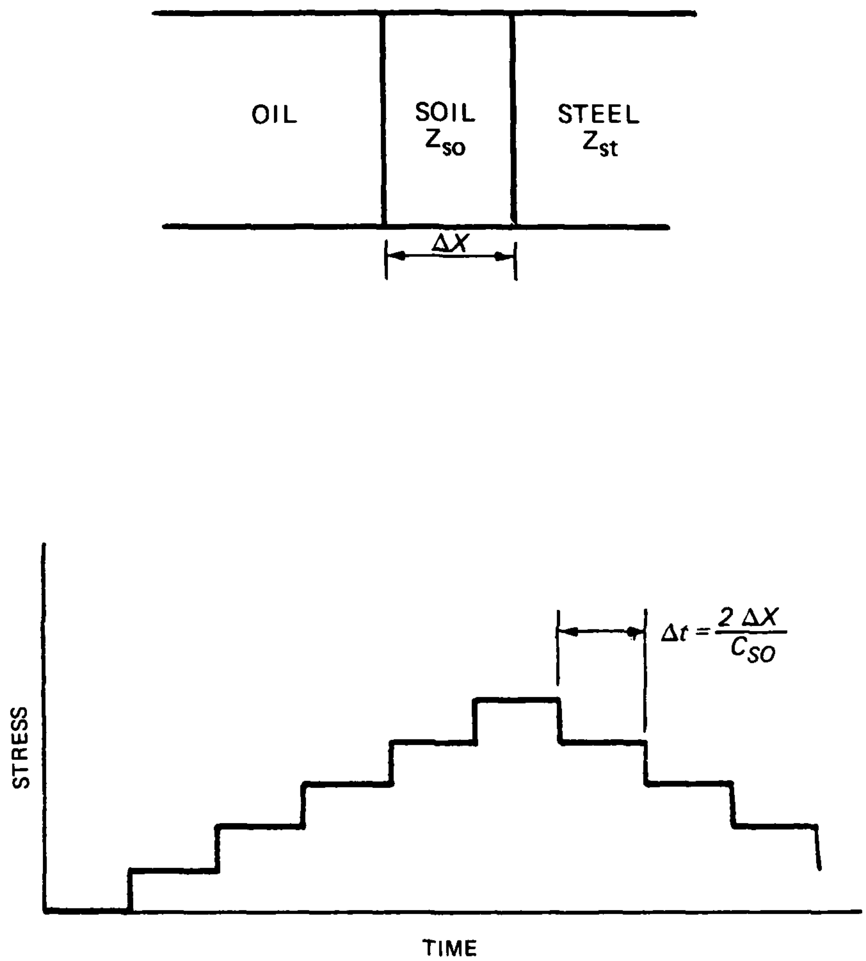


Figure 3 Configuration of oil, soil and steel base considered in the one-dimensional strain analyses, and gradually rising loading consisting of several reverberations of waves through the soil

where $\Delta\sigma_1$ is the stress amplitude of the incident wavelet and Z_{so} and Z_{st} are acoustic impedances (ρC) of the soil and steel. For steel Z_{st} is 4.7×10^6 g/cm/sec and for soils Z_{so} ranges from 8×10^3 to 1.2×10^5 g/cm/sec for stresses below 1 kbar. Thus, the factor $2 \times Z_{st} / (Z_{so} + Z_{st})$ is approximately 2.0 for all soils. Hence, the reflected wave is doubled at the base of the sample. This wave returns to the top of the soil and is again reflected, but this time as a rarefaction wave, reducing the amplitude of the wavelet to that of the applied stress in the oil. In the elastic case, the wavelet would continue to oscillate indefinitely, but we may presume that the wave will actually dissipate in the soil. Therefore, we assume that $2 \times \Delta\sigma_1$ is the largest amplitude of the wavelet and that this stress occurs at the base of the specimen.

The accuracy of the entire wave can now be determined by summing these wavelets. If the entire stress loading were applied within one transit time through the specimen, the stress overshoot would be double the applied stress and that would produce an unacceptable stress variation. If we apply the stress more slowly, the overstress $\Delta\sigma_2$ will be a smaller fraction of the peak stress. If the overstress is a fraction f of the peak stress, then the stress will rise in 1/f steps during 2/f wave transits through the soil. The transit time through the soil is simply $\Delta X/C$, where ΔX is the soil thickness and C is the wavespeed (longitudinal velocity). Therefore, the rise time of the applied stress is

$$t_r = \frac{2 \cdot \Delta X}{fC} \qquad (2)$$

To apply the results of this analysis to the soil tester problem, consider a 1/2-inch sample of sand with a wave speed of 5×10^4 cm/s. In this case, the minimum rise time is 0.25 ms for f = 20%. For clay, with a wave speed of 8.5×10^3 cm/s, the minimum rise time is 1.5 ms. These results correspond fairly well with our expectations from our review of the experimental data. The relationship between rise time, wave speed, and overstress calculated using equation (2) is shown in Figure 4.

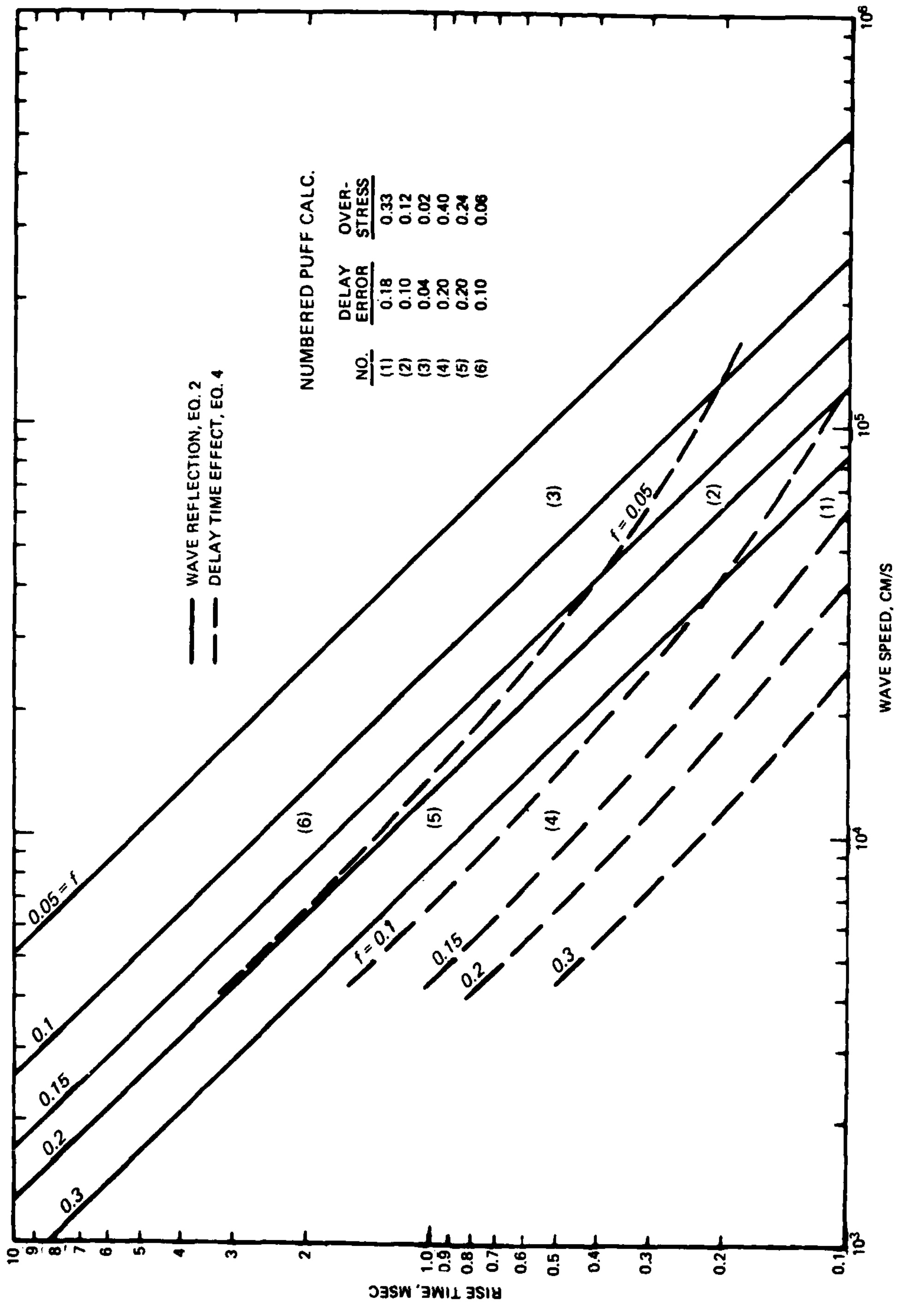


Figure 4 Errors in the stress-strain relation

Next, we perform an approximate analysis of the effects of the time delay between the arrival of the wave front at the gage locations and at the midpoint of the soil sample. The pressure is measured in the oil about 1 cm above the soil surface. The strain is interpreted from the displacement transducer at the soil surface. This difference in gage locations leads to an apparent time delay between the stress and strain and thus to a hysteresis loop in the stress-strain relation. The delay time for the pressure gage is simply the travel time of the wave through 1 cm of oil and one-half of the soil thickness. This time delay is

$$t_d = \frac{\Delta X_o}{C_o} + \frac{\Delta X_{so}}{2C_{so}} \tag{3}$$

The delay time for the displacement gage is more difficult to estimate because the gage begins to respond when the wave arrives at the soil surface, but does not reach the registration of the full strain until after the wave has reverberated several times through the soil. Thus, the main effect of the displacement gage is to spread the wave front; this effect is partially included in the description of wave reflections, which was treated above. Therefore, for this analysis we consider the time delay from equation (3) as the total delay.

The time delay from equation (3) causes an apparent hysteresis loop in the stress-strain relation, as shown in Figure 5. The relative error in stress, $\Delta\sigma/\sigma_{max}$, is proportional to the delay time divided by the rise time of the wave:

$$f = \frac{\Delta\sigma}{\sigma_{max}} = \frac{t_d}{t_r} \tag{4}$$

where t_r is the rise time and σ_{max} is the peak stress. In Figure 4, the relative error in stress is shown as a function of rise time and wave velocity in the soil. (The wave velocity in the oil is taken as 1.89 km/s.) Comparing the curves in Figure 4 shows that the error associated

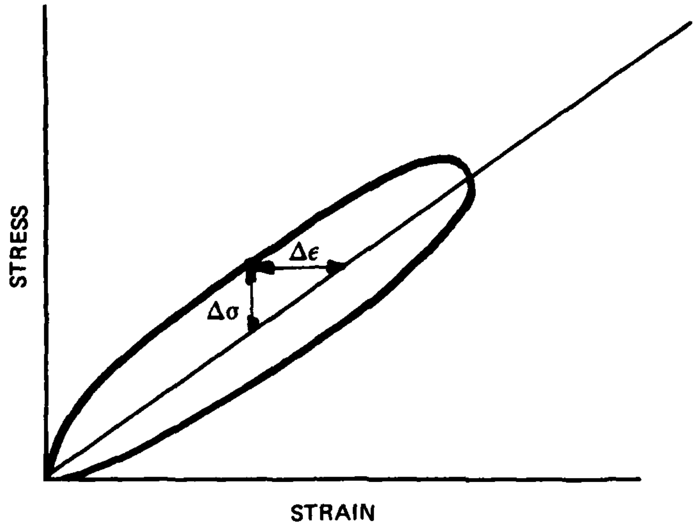


Figure 5 Apparent hysteresis loop in a stress-strain relation caused by a time delay between the stress and strain signals.

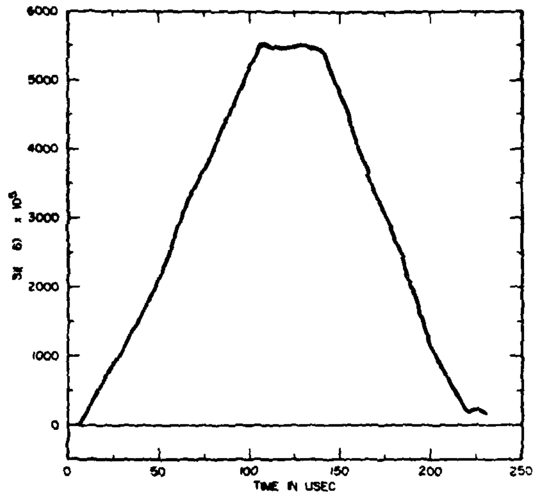
with the delay time has a similar variation to that associated with the reflection from the base plate but is somewhat smaller.

One-Dimensional Wave Propagation Code Analyses

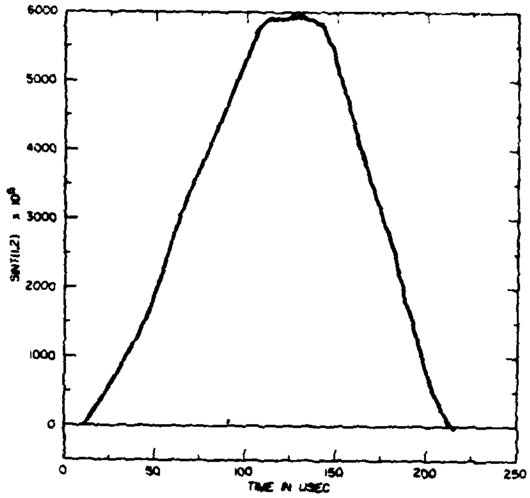
Our one-dimensional wave propagation code SRI PUFF 8[4] was used to simulate the experimental chamber of the tester. Included were 2 cm of the oil chamber (1 cm above and 1 cm below the pressure gage), the soil specimen (0.5 inch thick), and a 6-inch steel base. The stress was applied in the form of a trapezoid with a loading ramp, a constant stress interval, and an unloading ramp. With these calculations we were able to examine how well the pressure gage reading follows the loading on the soil and how well the measured pressure-displacement relation corresponds to the true stress-strain relation.

Calculations were performed with a range of stress rise times applied at the top of the soil. Two soils with bulk moduli of 5 kbar and 0.2 kbar (corresponding to the sand and clay used at WES) were simulated. Although these soil models are elastic, these properties seemed reasonable for a preliminary study. Elastic behavior tends to emphasize the wave effects and thus to help clarify the problems to be studied. Additional calculations should be conducted with more representative hysteretic and rate-dependent soil models.

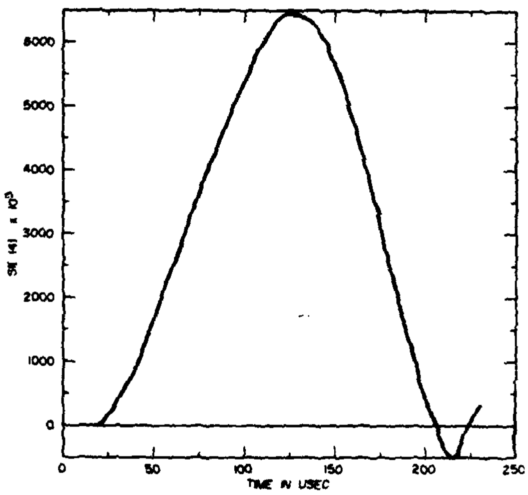
Some of the results of these simulations are shown in Figures 6 through 9, which compare measured pressure records and average stresses in the soil, average strain with the measured displacement, and the pressure-displacement with the stress-strain relation. At the high stress rates, it is clear that the measured pressure leads the stress in the soil by 10 to 20 μs. For the longer loading durations, these PUFF calculations indicate that the steel plate has begun to move significantly so that the surface displacement of the soil does not return to near its origin, but continues to move. To approximate the average soil strain, we calculated the instantaneous soil thickness from the PUFF output. When the oil pressure at the gage location was compared with



STRESS AT OIL
PRESSURE GAGE (DYN/CM2)

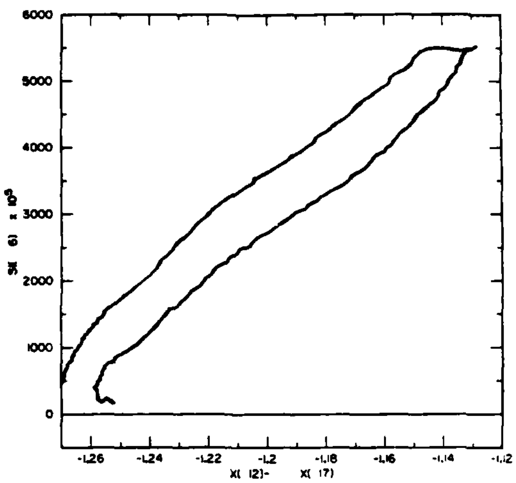


STRESS AT OIL-SOIL
INTERFACE (DYN/CM2)

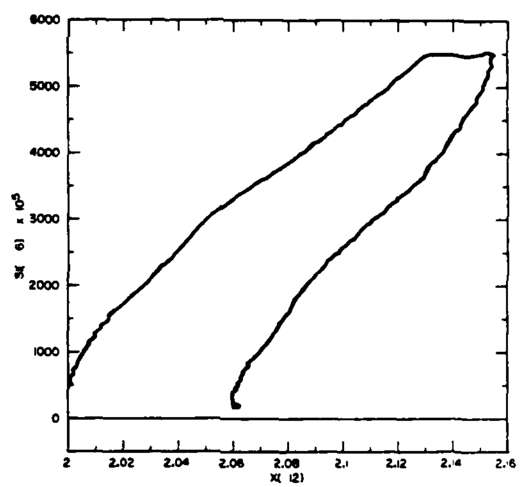


STRESS IN MIDST OF
SOIL SAMPLE (DYN/CM2)

Figure 6 Stress at several locations in PUFF calculation simulating a 0.5 kbar loading with a 0.1 msec rise time onto sand



OIL PRESSURE VS SOIL THICKNESS
(DYN/CM2 VS CM)



OIL PRESSURE VS DISPLACEMENT
AT SOIL SURFACE (DYN/CM2 VS CM)

Figure 7 Computed stress-strain paths for 0.1 msec rise in sand. Pressure at the oil gage plane is plotted against soil sample thickness and against the displacement of the top of the soil.

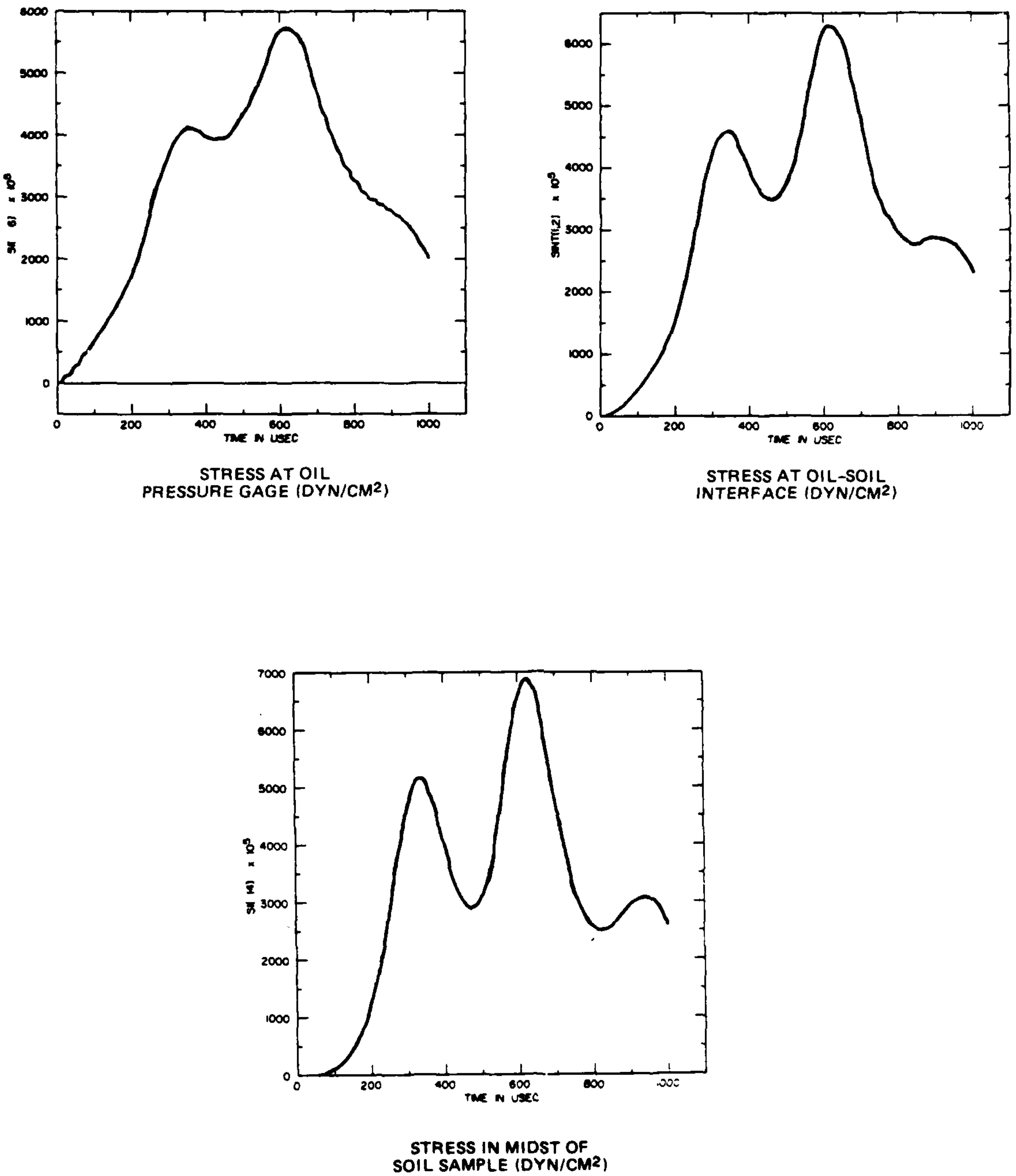


Figure 8 Stress at several locations in PUFF calculation simulating a 0.5 kbar loading with a 0.5 msec rise time onto clay

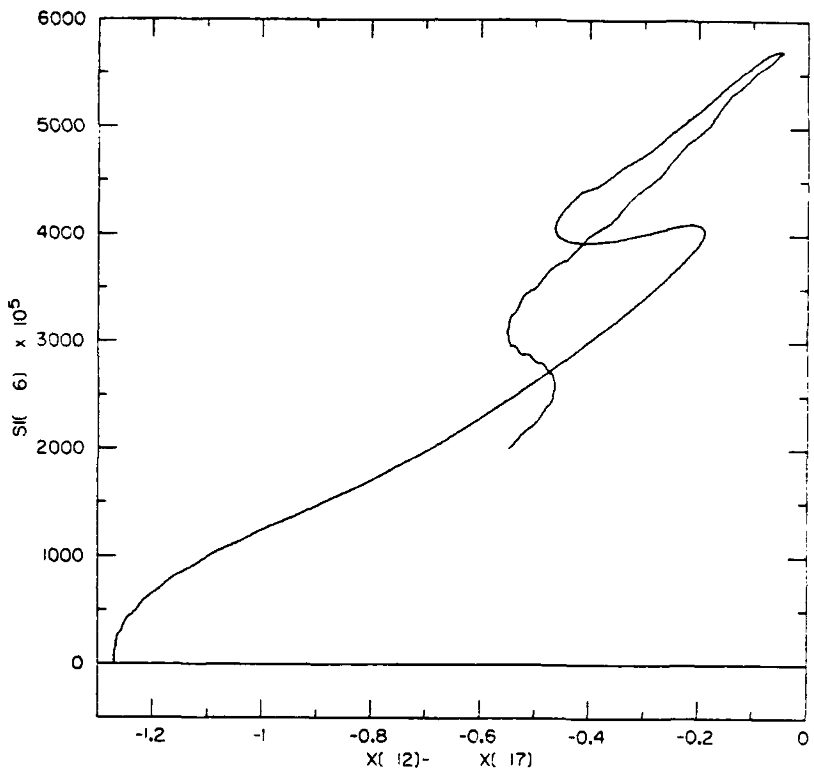


Figure 9 Computed stress-strain path for 0.5 msec rise in clay. Pressure in dyn/cm^2 at the oil gage plane is plotted against soil sample thickness in cm.

this "average strain," results such as those in Figures 7 and 9 were obtained. This "average strain" is a better strain measure than the displacement at the soil surface, so these figures probably show less hysteresis than would be obtained if a more complete (two-dimensional) simulation of the problem were conducted. Thus it is apparent that the displacement-pressure measurement suffers from two problems:

- The pressure and displacement measurements do not correspond to the same time.
- Soil particles at different depths in the specimen traverse different stress-strain paths.

By limiting the rise of the stress suitably, we can bring both of these inaccuracies within acceptable limits. The errors obtained in the PUFF calculations are shown in Figure 4 with the analytical results. The delay error effect and overstress error are listed separately although they are comparable. These numerical results can also be compared with the results of equation (2) and (4), also shown in Figure 4. Generally, equation (4) underestimates the error and equation (2) overestimates it. However, equation (2) is close enough for planning experiments.

Lateral Expansion

In a true uniaxial strain experiment, there is no lateral expansion. The thick steel chamber of the UX test device provides considerable confinement, but nevertheless some expansion occurs. This expansion is approximately

$$\varepsilon_r = \frac{\sigma_r}{2G} \qquad (5)$$

where σ_r is the radial stress and G is the shear modulus of the steel. Only the resistance of the steel annulus around the soil is considered; therefore, ε_r from equation (5) must be an upper bound on the lateral expansion that would actually occur. This expansion will reduce the axial stress in the soil by an amount that can be estimated from elastic relations:

$$\Delta\sigma_a = -(2K_{so} + \frac{4}{3} G_{so})\,\varepsilon_r \tag{6}$$

Dividing the stress reduction $\Delta\sigma_a$ by σ_r from equation (5), we obtain an estimate of the fractional error in stress:

$$\frac{\Delta\sigma_a}{\sigma_r} = -\frac{K_{so} + \frac{2}{3} G_{so}}{G} \tag{7}$$

To keep the fractional error below 10%, the longitudinal modulus of the soil [actually $K_{so} + (4/3)\,G_{so}$] should be less than 80 kbar. This condition is easily met by the soils and stress levels being considered at WES.

DATA REDUCTION PROCEDURE

Computer simulations have been performed to verify the stress-strain relations obtained from the UX test devices. Computed oil pressures and displacements have been compared with the average stress-strain path in the soil to determine how well the measured pressure-displacement relation represents the soil stress-strain relation. Two computer programs, ONED and ONED3P, are currently being used in these simulations. Here we discuss the overall strategy of the data reduction, the computer programs and their applicability to wave propagation problems, and the material property subroutines in these programs.

Overall Strategy

The solution procedure that is used to obtain stress-strain relations from the measured data seems to be appropriate for the present device and testing rates. In an ideal test procedure, the measurements that are obtained in the test device are processed computationally and converted to the desired stress-strain relations. For example, in wave propagation experiments, stresses and particle velocities are measured at several depths through a specimen. These measured histories are converted to stress-strain relations through an integration method termed a Lagrangian analysis. However, no procedure as the Lagrangian analysis has been developed for the uniaxial strain conditions of our test device. Therefore, the indirect method must be used: estimate the stress-strain relations, simulate the experiment, and compare the simulated results with the measured data. Hence, it is necessary to have both a suitable computer program for simulating the UX test conditions under high rate loading and a model representing the stress-strain relations that are expected for the soil.

Computer Programs

In the following discussion of the computational procedure, the computer programs are separated into two parts:

(1) Motion calculational procedure (finite element or finite difference wave propagation code).

(2) Material property subroutine (stress-strain relation).

We make this division because the two parts are distinct in most modern wave codes. With this separation, when a new material property subroutine is developed by some agency, it can be sent to other researchers, who can insert it into their wave code. Thus the other workers do not need to acquire another wave code, but only the new material property routine.

Motion Codes

ONED. The small structural analysis code ONED was written to handle time-dependent loading, but not shock loading.[5] It treats linear elastic behavior, but also has an iterative solution procedure that can be used for slightly nonlinear material properties. Because it does not treat shock behavior, ONED is not appropriate for handling wave propagation in the highly nonlinear soils studied at WES. ONED uses an implicit (matrix inversion) solution procedure, which is appropriate for problems where waves are not of interest and large time steps can be used. In the current context, the waves are important and they govern the time step; therefore, an explicit calculational procedure should be used.

ONED3P. The small finite-element code ONED3P was written to handle wave propagation under conditions of small deformation and without shocks.[6] The basic structure seems appropriate for simulating high rate loading in the uniaxial test device, but some modifications are recommended:

(1) Adjust the time sequencing of the displacement, velocity, acceleration, and stress calculations so that they provide an accurate centering of the finite difference equations for

momentum conservation. This sequencing is given in detail in Section 3.1 of the PUFF Manual (Ref. 4).

(2) Modify the treatment of strain and density to represent a large displacement formulation.

(3) Incorporate echo printing so that the input quantities are listed with their names.

(4) Add the calculation of an artificial viscosity with both a quadratic and a linear term in $d\rho/dt$. These viscous stresses are described in Section 3.3 of the PUFF Manual (Ref. 4).

(5) Isolate the subroutines that handle the stress-strain calculation so that these subroutines can be transported to other organizations and so that other routines can be readily added.

With these modifications ONED3P will be able to handle the planar one-dimensional calculations required. Note that there is no internal energy calculation in the code so that the stress levels should be limited to shock strengths well below the range of melting and vaporization.

There are great advantages to using a code that is well understood by resident researchers. Therefore, ONED3P, with the modifications suggested above, is recommended for wave propagation calculations at WES.

Other Codes. WES personnel may wish to consider other one-dimensional codes if their work extends beyond the current types of calculations. Among those available are WONDY[7] and SRI PUFF 8,[4] both of which are well-documented and include additional features that may be required. They treat explosives, impacts, and thermal radiation problems. A great range of material models are available, and several may be used in a single problem. Cylindrical and spherical flows can be handled as well as planar. The cell sizes can vary gradually through a material as well as from layer to layer. Rezoning (an alteration of the element sizes to provide more uniform sizes) can be performed to minimize computational time when small elements are required to define shock fronts at early times in the problem. Internal energy, melting, and vaporization are also handled.

Material Models and Subroutines

Two material models are currently being used with the ONED[5] and ONED3P[6] codes. They both exhibit the nonlinear, hysteretic behavior common to soils. In these models, the loading stress-strain path is concave upward so that the material stiffens under increasing stress. During unloading the stress follows a nonlinear path that differs from the loading path, but the path is also concave upward. The unloading path lies under the loading path so that not all the strain is recovered during unloading. This lack of recovery means that the soil is absorbing energy during loading cycles and that stress pulses will attenuate as they pass through the soil.

In addition to the nonlinear hysteresis, the model used in ONED3P has a strain-rate dependence represented by a dashpot. This rate effect causes the loading and unloading to occur on somewhat steeper stress-strain curves than they would without the rate effect. Both the hysteresis and the rate effects represent real behavior observed in the sand and clay being studied at WES. Both are one-dimensional models in that they do not provide for any loading paths except those in uniaxial strain and even do not provide the lateral stress in that case. Because only one stress quantity is measured in the UX test, these models do represent all the data available in the test.

An elastic-viscoplastic cap model is also being developed at WES to represent soils data. This model has a nonlinear elastic behavior (both bulk and shear moduli are functions of the stress level), a plastic response with two yield curves (one for shear failure and one for compaction), and a rate-dependence associated with the plastic behavior. Because of the rate-dependence, the positions of the two yield curves depend on the loading rate. There are six elastic constants, seven plastic constants, and three constants associated with the rate effects. As shown in Ref. 8, this model is able to fit laboratory data fairly well. It is a three-dimensional model and therefore can be used in ground motion calculations for complex loadings and geometries.

Unfortunately, fitting the model to the data is not easy; in fact, the model requires more data than are actually available in even a complete set of static and dynamic tests. Hence, some of the parameters must be merely estimated. This cap model has not been used with either of the computer programs, but it will probably be attached to one of them soon. We recommend that it be inserted into ONED3P.

SUMMARY

This review of the WES explosive-loaded one-dimensional soil testing device and the associated data reduction procedure has brought no surprises, but has verified the expected requirements for the conduct of the soil testing. However, the review has helped to clarify the test requirements and indicate what needs to be done to reach faster strain-rate conditions.

For the test device, it will be necessary to limit the rise times used depending on the accuracy required and the soil stiffness. A chart (Figure 4) was developed that allows an estimation of the accuracy obtainable. The sources of the inaccuracies are:

- Differences in location of the pressure and displacement gages.
- Reflection of waves from the base, which produces a non-uniform stress state in the sample.

The results of the soil tests at WES suggest that there are real material rate effects occurring in the soil in addition to these measurement effects, which often appear like soil rate effects. Thus, testing devices are needed that can be used to study these material rate-effects.

The present data reduction procedure is a valid approach to determining the true material properties from a test device that is operating at the limit of its capabilities. For longer rise times, the stress-strain data from the experiments can be used directly as the stress-strain relation for the model. For the faster rise times when wave effects cannot be disregarded, the model can be used to simulate the test and the results compared with the experimental data. This approach allows the device to be used for removing the wave effects while these effects are a small fraction of the measured amplitudes. However, the approach cannot be used when the wave effects dominate the measurements.

From our examination of the computer codes ONED and ONED3P, we determined that ONED3P could be readily modified to produce a true wave propagation code.

The linear and nonlinear hysteretic models used in one-dimensional calculations are easily fitted to data and actually represent the data quite well. Unfortunately, they are one-dimensional and therefore cannot be readily used in the large-scale two- and three-dimensional calculations for which the materials data are required. The cap model under development is three-dimensional in character, but has the handicap of having too many undeterminable parameters. An intermediate level model with the simplicity of the hysteretic models plus rate-dependence and a three-dimensional character should be developed to supplement these available models.

RECOMMENDATIONS

On the basis of our review of the test device and the data reduction procedures, we make the following recommendations for soil testing at WES.

Test Device

The current test device must be used within the limitations outlined in Figure 4 of this report. The major limitation at high loading rates with the tester are intrinsic to the system and cannot be eliminated by adjustments in measurements or in the test device.

Hysteretic Model

The current hysteretic model should be extended to a three-dimensional form with rate effects. The three-dimensionality can be incorporated simply by separating pressure and deviatoric stress. The rate effects can be included either as a simple stress-relaxation model or explicitly as fluid flow and pore collapse mechanisms. A model termed PEST[9] that was developed several years ago for representing porous metals and ceramics, meets these requirements. These new features can be readily added to the hysteretic models now in use. The fitting can be performed by using data obtained from several testing rates. The hysteretic parameters are determined at the low rates (several millisecond loadings), and the rate effects can be determined from the high rate tests. Shear properties (for the deviator stresses) must be determined by auxiliary measurements, such as those from lateral gages in the UX device, or from triaxial experiments.

Wave Code

Make ONED3P a fully capable wave code for soils by adding artificial viscosity, large deformation strain determination, and separability of the material models from the code.

High Rate Tests

The foregoing recommendations merely show how to make optimum use of the current testing devices and methods that are certainly limited to rise times of 0.1 ms for sand and 1 ms for clay. The major concern is to reach rise times of 10 to 100 μs, such as those experienced in actual ground motion tests. For such rise times, a special device is needed. Present gas guns cannot be used because they usually have too short a test duration or use too small a sample or both. However, the experiment should be a wave propagation experiment; that is, the measurements should all occur during the transit of one wave because this matches the ground motion conditions to be simulated. The samples should be somewhat larger than those used in the current UX tester: probably 1 to 2 inches thick and 8 to 12 inches in diameter. Velocity and pressure gages should be embedded at intervals in the soil. This new test poses several development problems:

- Loading device. A uniform pressure must be applied over the entire soil surface. The rise of the wave must be monotonic, and the decay of the pressure must occur in times only slightly longer than the rise. Such loads might be obtained with an explosive driving a piston under conditions that allow free expansion of the gases behind the piston.
- Gaging. Foil gages can now be made with compensation for bending and strain. However, calibration methods and armoring techniques for stress gages would need to be verified for the soil being used. For the magnetic foil velocity gages, an open testing chamber or a well-calibrated closed chamber is needed.

- Data reduction. A so-called Lagrangian analysis procedure[10] is commonly used to determine the stress-strain relations from the stress and velocity records. The present computer code for this analysis at SRI uses either stress or velocity, or a combination. Because more reliable results can probably be obtained with the combination of records, the combined analysis should be further developed.

The foregoing outline of the development of a new test procedure shows the direction that should be taken. This may be a long-range plan, but it is one that will truly account for both rate effects in the soil and also wave effects in the testing devices.

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